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Assessing the Natural and Anthropogenic Radionuclide Activities in Fish from Arctic Rivers (Northwestern Russia)

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ABSTRACT

This scientific article presents the results of studies on the distribution of natural and artificial radionuclides in fish living in the rivers of the northwestern sector of the Arctic zone of the Russian Federation. Fish sampling (about 76 kg in total) was carried out in the White Sea, in the Northern Dvina and Mezen Rivers, and in the Sukhoe Sea Bay of the Arkhangelsk Region, as well as in the rivers of the Nenets Autonomous District: Pesha, Oma, Vizhas, Nes, and Pechora. The results showed the presence of artificial radionuclides Cs-137 and Sr-90 in fish only in the Nes River of the Nenets Autonomous District. The levels of radionuclides in whole bodies perch and pike in the Nes River range from 3.73 to 14.0 Bq/kg wet weight for Cs-137 and less than 3.72 to 23.1 Bq/kg wet weight for Sr-90. In addition to Cs-137 and Sr-90, the presence of the radionuclide K-40, which is the main dose-forming radionuclide, was noted in the fish of all the studied rivers and seas. K-40 activity was in the reached values 138 Bq/kg for whole fish bodies. The only assumption that can explain the presence of artificial radionuclides in the fish of the Nes River is a possible radioactive trace formed as a result of global nuclear tests, including in the Novaya Zemlya archipelago. At the same time, it is noted that the current levels of technogenic radioactivity in fish from the Nes River do not pose a radiological hazard to the local population.

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INTRODUCTION

Since the beginning of peaceful and military nuclear explosions, the Arctic territories have been exposed to artificial radioactivity (UNSCEAR, 2000). The main sources of technogenic radioactivity were radioactive fallout after nuclear tests, including on the Novaya Zemlya archipelago, pollution from Western European radiochemical plants in Great Britain and France; consequences of the Chernobyl accident in 1986 (Smith et al., 2000; Strand et al., 2002; Gwynn et al., 2004; Dowdall et al., 2005; Łokas et al., 2013; Matishov et al., 2014). In Russia and the world as a whole, attention is mainly paid to monitoring the environment in the Northern Hemisphere due to the high pollution caused by global nuclear fallout and relatively slow atmospheric mixing in the longitudinal plane of the Earth (Livingston and Povinec, 2002; Friedlander et al., 2005). Thus, the northwestern part of the Arctic region of Russia is distinguished by a large number of anthropogenic sources of radionuclides, that can pollute the territory (Friedlander et al., 2005; Yakovlev and Puchkov, 2020; Yakovlev et al., 2021; Yakovlev et al., 2022).

These facts and events have consequences for the fauna of the Arctic territories. So there is intensive radionuclide accumulation in fish as a result of contamination of soil, water bodies and bottom sediments (Friedlander et al., 2005; Giri et al., 2010; Abdullah et al., 2015; Adel et al. 2018). In this regard, fish can be a bioindicator of the presence of natural and technogenic

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radionuclides in natural environments (Alimova and Utkina, 2016; Trapeznikov et al., 2019).

One of the main technogenic pollutants of fish resources is long-lived radionuclides: Cs-137 ($T_{1/2}$ = 30.1 years) and Sr-90 ($T_{1/2}$ = 28 years) (Trapeznikov et al., 2019; Milenkovic et al., 2019). These radionuclides are fission fragments, which have the highest yield during the fission of nuclear fuel based on uranium and plutonium radionuclides. The presence of Cs-137 and Sr-90 in the natural environment is due to the modern activities of enterprises that are involved in the management of radioactive waste, stationery and transport nuclear power plants, and objects of the "nuclear legacy" (testing of nuclear weapons, "peaceful" nuclear explosions, etc.) (UNSCEAR, 2000). The radionuclide Sr-90 is highly soluble in water and exhibits a relatively high absorption ability by marine organisms due to having similar chemical properties to calcium (Suzuki et al., 1979; Bezhenar et al., 2021; Fakhri et al., 2022). Radiocesium is not essential for biota, but is taken up by fish in food and water (Suzuki et al., 1979; Pinder et al., 2011; Thomas et al., 2018) due to its chemical similarity to potassium (Zotina et al., 2019; Fakhri et al., 2022).

In addition to artificial radionuclides, fish can accumulate radionuclides of natural origin. First of all, the radionuclide K-40 is contained in the aquatic environment, bottom sediments, crustaceans and aquatic vegetation, etc. The content of K-40 in the components of the natural environment directly depends on the geological structure of the territory, geochemical composition, climate-forming factors, as well as anthropogenic interference as a result of various human activities (Milenkovic et al., 2019). According to the International Atomic Energy Agency, the total radioactivity of the marine environment is mainly due to potassium (UNEP/IAEA, 1992; IAEA, 1999).

Taking into account the complexity of natural and climatic conditions, the inaccessibility of most of the territory of the Arctic region of Russia, but at the same time the ever-increasing level of economic activity, the relevance of assessing the environmental parameters of aquatic biological resources remains at a high level. At the same time, in the presence of a large number of nuclear and radiation hazardous objects, the assessment of radiation parameters prevails over other parameters of environmental pollution (Muratov et al., 2014).

In connection with the above, the purpose of this study is to establish the level of radioactive isotope content in fish in the rivers of the northwestern segment of the Russian Arctic, as well as to identify ways of distributing radionuclides in organs and tissues in fish.

MATERIALS AND METHODS

The sampling of fish was carried out in two stages. In the first stage, from March 2019 to August 2020, fish sampling was carried out in the White Sea, the Northern Dvina, Pesha, Oma, Vizhas, and Nes Rivers. The following fish species were selected: whitefish (*Coregonus lavaretus*), bream (*Abramis brama*), smelt (*Osmerus eperlanus*), flounder (*Pleuronectiformes*), sculpin (*Myoxocephalus scorpius*), saffron cod (*Eleginus nawaga*), perch (*Perca fluviatilis*), and herring (*Clupea harengus*). The total weight of the samples was 32.8 kg. The main goal of the first stage of research was the reconnaissance radioecological research of fish in the region under study. Based on the results of the first stage, key areas for additional sampling were identified. Such areas were the Mezen River (Arkhangelsk Region) and the Nes and Pechora Rivers (Nenets Autonomous District). The following fish species were selected: perch, pike (*Esox lucius*), ide (*Leucis cusidus*), and roach (*Rutilus rutilus*). The total weight of the samples was 43.0 kg. A feature of the second stage of research was the separation of samples not only by fish species, but also into separate organs and tissues (muscle tissue, bone tissue, scales, fins, heads, and entrails). The fish sampling sites are shown in Fig. 1.

After delivery to the laboratory, fish samples were dried in a BINDER E28 oven and then ashed at a temperature not exceeding 400 °C to avoid the loss of radionuclides, especially Cs-137. The analytical procedures are described below.

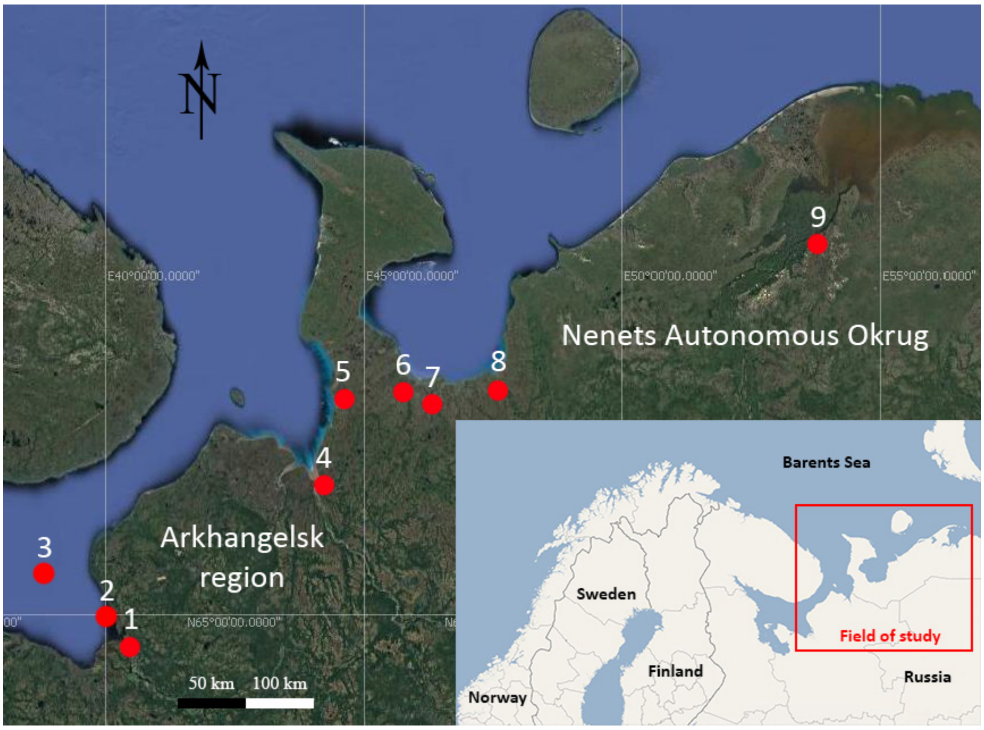

Fig. 1. Fish sampling sites
(1 – Northern Dvina River, 2 – Sukhoe Sea Bay, 3 – White Sea, 4 – Mezen River, 5 – Nes River, 6 – Vizhas River, 7 – Oma River, 8 – Pesha River, 9 – Pechora River)

Gamma spectrometry measurements.

The radionuclides Cs-137 and K-40 were determined using an ORTEC low-background semiconductor gamma spectrometer (USA), based on a GEM40 coaxial detector with high purity germanium (HPGe), and SpectraLine software. The resolution of the gamma spectrometer along the 1.33MeV (Co-60) was 1.75 keV, and the relative efficiency was 40%. A 1 liter Marinelli vessel and plastic beakers of different volumes were chosen as working geometries for measurements. The measurement time was chosen in the range of 2 to 5 hours. The minimum detectable activity (MDA) at time exposure t = 7,200 s for the Marinelli geometry for the detector GEM40 made up for K-40 – 7.0 Bq and Cs-137 – 0.08 Bq. The absence or presence of a radionuclide in the sample means that the activity of the sample does not exceed or exceed, respectively, the level of the MDA. The MDA in this study is determined by the spectrometric and radiometric systems and methods used by the authors, as well as by the characteristics of counting samples (wet weight, counting sample geometry, etc.). The measurement uncertainty was no more than 20% (depending on the activity value of the determined radionuclides).

Total alpha/beta activity measurements

The parameters of total activity in terms of alpha and beta radiation were determined using an alpha-beta radiometer RKS-01 "Abelia" (NTC Amplitude, Russia) and 10-channel low-level planchet counter LB 770 (Berthold Technologies GmbH and Co. KG, Germany)

A counting sample for measuring total alpha and beta activity was a metal plate with 1 gram of an ashed fish sample. We made 2 counting samples for each sample. The calculation of the total alpha, beta activity was carried out according to the following formula:

$$A_{total\_alpha(beta)} = \frac{N_s - N_b}{Eff \times M \times K_{abs}}$$

where:

$A_{total\_alpha\ (beta)}$ is the total activity of alpha (beta) radiation in the sample, Bq/kg;

N_s is the rate of alpha- (beta-) sample counting on the radiometer, counts/s;

N_b is the rate of alpha- (beta-) background counting on the radiometer, counts/s;

Eff is the efficiency parameter of the radiometer for the energy of alpha (beta) radiation in accordance with the technical parameters of the radiometer, %;

M is the mass of the counting sample, kg;

K_{abs} is the coefficient of absorption of alpha (beta) radiation in a counting sample, %.

Radiochemical sample preparation and determination of Sr-90

The determination of the Sr-90 radionuclide was carried out based on its daughter decay product, Y-90. In our study, we considered that the Sr-90 and Y-90 radionuclides are in radioactive equilibrium. After radiochemical isolation of Y-90, we determined the half-life of beta radiation in the counting sample within 10-14 days. If we obtained a half-life of about 64 hours, then the preparation of the counting sample was considered successful. If the calculated half-life was different from 64 hours, the radiochemical isolation was repeated.

The calculation of the activity of Sr-90 after measuring the radiochemically isolated Y-90 was carried out according to the following formula:

$$A_{sr90} = \frac{N_s - N_b}{Eff \times M \times ChLos \times K_{abs}}$$

where:

A_{sr90} is the specific activity of Sr-90 in the sample, Bq/kg;

N_s is the sample counting rate on the radiometer, counts/s;

N_b is the background counting rate on the radiometer, counts/s;

Eff is the efficiency parameter of the radiometer for the Y-90 beta radiation energy (E = 2260 keV), %;

M is the mass of the counting sample, kg;

ChLos is the chemical losses of Y-90, %;

K_{abs} is the coefficient of absorption of beta radiation, %.

After radiochemical preparation, Sr-90 was determined using an alpha-beta radiometer RKS-01 “Abelia” (NTC Amplitude, Russia) and 10-channel low-level planchet counter LB 770 (Berthold Technologies GmbH and Co. KG, Germany). Additionally, samples in which Sr-90 radionuclide was detected were measured on Beta-1C beta-spectrometers with a scintillation detector (JSC SPC ASPECT, Russia).

Calculation of the ingestion dose from radionuclides

According to the International Commission on Radiological Protection (Age-dependent doses to the Members…, 1996), the ingestion dose from radionuclides is given by:

$$H_{T,r} = \sum U_i \cdot C^r \cdot g_{T,r},$$

where the coefficient U_i represents the rate of consumption (kg/year); C^r – radionuclide concentration r (Bq/kg), $g_{T,r}$ – dose conversion factor when a radionuclide enters the tissue T (Sv/Bq). For adults, the recommended dose conversion factor $g_{T,r}$ for K-40 is $6.2 \cdot 10^{-9}$ Sv/Bq, for Cs-137 – $1.3 \cdot 10^{-8}$ Sv/Bq, for Sr-90 – $2.8 \cdot 10^{-8}$ Sv/Bq (Compendium of dose coefficients…, 2012).

Quality control of measurements

The determination of the radionuclides was carried out in the laboratory of environmental radiology of the N. Laverov Federal Center for Integrated Arctic Research of the Ural Branch of the Russian Academy of Sciences (Russia, Arkhangelsk), which complies with the accreditation criteria for testing laboratories established in ISO/IEC 17025. The laboratory has a wide range of reference radionuclide sources for equipment calibration and quality control procedures for measurements. Calibration and quality control of gamma spectrometric measurements is carried out using disk type sources OSGI-P and special volumetric activity measures – Marinelli Beakers with different density (RITVERC, Russia-Germany). Calibration, registration efficiency control, quality control of beta-radiometric measurements and radiochemical preparation are carried out using standardized (reference) radionuclide solutions (RITVERC, Russia-Germany).

Each reference radionuclide source or solution has a calibration certificate.

RESULTS AND DISCUSSION

The first stage of research. Reconnaissance radioecological research of fish

In the first stage of the study, the analysis of fish resources was carried out in order to detect artificial radionuclides in fish of various species in the rivers Northern Dvina, Pesha, Oma, Vizhas, Nes, in the Sukhoe Sea Bay and the White Sea. The research results are presented in Table 1A.

The total β-activity in fish samples ranged from 49.2 to 143.2 Bq/kg with the highest values in pooled fish samples (perch, flounder and saffron cod) from the Vizhas River (125.7–143.2 Bq/kg) and in a sample of saffron cod from the Nes River (135.6 Bq/kg) (Table 1A). The data are similar to some of the results obtained by other researchers. So, for example, earlier studies in the Dnepropetrovsk reservoir established the total β-activity of fish at a level of 58.08 Bq/kg (for carp) to 138.84 Bq/kg (for eastern bream) (Hubanova et al., 2019). Alpha-emitting radionuclides are found in small quantities. The values of specific α-activity are below 7.1 Bq/kg and are reliably determined only for whitefish from the Northern Dvina River and flounder from the Sukhoe Sea Bay.

As a result of the studies, the presence of artificial radionuclides Cs-137 and Sr-90 in some fish samples was revealed (Table 1A). The activity of the Cs-137 isotope was in the range from <0.12 to 13.4 Bq/kg. The highest activity of the isotope was found in a perch sample from the Nes River (11.7–13.4 Bq/kg).

In the present study, the content of the Sr-90 isotope in fish varied from <1.3 to 29.1 Bq/kg (Table 1A). The highest values of Sr-90 activity were determined for perch from the Nes River (in the range from 18.6 to 29.1 Bq/kg).

The activity of the K-40 isotope ranged from 32.9 to 138.0 Bq/kg for the studied fish (Table 1A). According to previous studies, potassium is present in large quantities in sea-water and plays a key role in natural biochemical reactions in the body of fish, there-fore the concentration of K-40 in fish tissues is higher than that of other radionuclides (Ajayi et al., 2018). This radionuclide was the main dose-forming radionuclide in the studied samples of aquatic organisms and was the main contribution to the total beta-radiation activity. Maximum content of K-40 in study fish was noted in pooled fish samples (perch, flounder and saffron cod) from the Vizhas River (in the range from 110.1 to 138.0 Bq/kg), as well as in Saffron cod of the Nes River – 130.8 Bq/kg.

The second stage of the research. Distribution of radionuclides in individual biological systems of fish

The main results of the studies carried out at the second stage in the Nes, Mezen and Pechora Rivers are shown in Table 1A (Appendix A).

Whole fish samples (without separation into separate organs and tissues) were characterized by total β-activity in the range from 76.7 to 113.5 Bq/kg, α-activity at the level of the MDA (less than 12.6 Bq/kg), the activity of Cs-137 ranged from the MDA (less than 0.28) to 14.0 Bq/kg, the content of Sr-90 ranged from the MDA (less than 3.19) to 6.0 Bq/kg and K-40 in the range from 77.0 to 115.9 Bq/kg. The main dose-forming radionuclide in all fish samples was the natural radionuclide K-40, the content of which exceeded 86% of the total activity of beta-emitting radionuclides. The highest content of the Cs-137 isotope was observed for fish taken from the Nes River (3–14%). At the same time, for pike, the concentration of Cs-137 was 3.7 times higher than for perch. However, for perch, the highest content of the isotope Sr-90 (5%) was determined. No technogenic radionuclides were found in the fish of the Pechora and Mezen Rivers.

For a more detailed analysis of the studied fish, the selected fish were divided into 5 biological systems: fish heads, muscle tissue, bone tissue, fish entrails, a mixture of skin, scales, and fins. The results of radioecological studies of organs and tissues of perch and pike are shown in Figs. 2 and 3. The values of β-activity of organs and tissues vary within the following limits: from 93.4 to 142.1 Bq/kg for muscle tissue, from 94.5 to 151.8 Bq/kg for bone tissue, from 41.6 to 101.1 Bq/kg for a mixture of skin, scales and fins, from 48.2 to 79.9 Bq/kg for entrails, and from 55.1 to 96.9 Bq/kg for heads. In general, the largest accumulation of β-active radionuclides per weight was found in the muscle tissue of fish (from 49 to 51%).

The content of the Cs-137 isotope in organs and tissues is in the following activity ranges: from the MDA (< 0.21) to 19.5 Bq/kg for muscle tissue, from the MDA (< 0.46) to 17.9 Bq/kg for bone tissue, from the MDA (< 0.33) to 14.8 Bq/kg for a mixture of skin, scales, and fins, from the MDA (< 0.17) to 6.85 Bq/kg for entrails and from the MDA (< 0.24) to 9.38 Bq/kg for heads. According to the measurement results of the isotope activity in perch and pike from the Nes River, the maximum accumulation of Cs-137 (55% and 29%, respectively) is observed in muscle tissue. Cs-137 activity in bone tissue is slightly less than in muscle tissue (16% for perch and 26% for pike).

The Sr-90 isotope activity was below the MDA for muscle tissue (< 2.41 Bq/kg), for bone tissue (< 8.1 Bq/kg), and for entrails (< 3.3 Bq/kg). For skin, scales, and fins, the Sr-90 activity ranged from the MDA (< 3.32) to 21.67 Bq/kg, for heads – from the MDA (< 7.5) to 12.84 Bq/kg. The highest accumulation of Sr-90 was found in perch from the Nes River. Interestingly, the main accumulation of Sr-90 was noted for a mixture of skin, scales, and fins (47%) and for heads (33%). For other fish samples, higher values were also noted for head

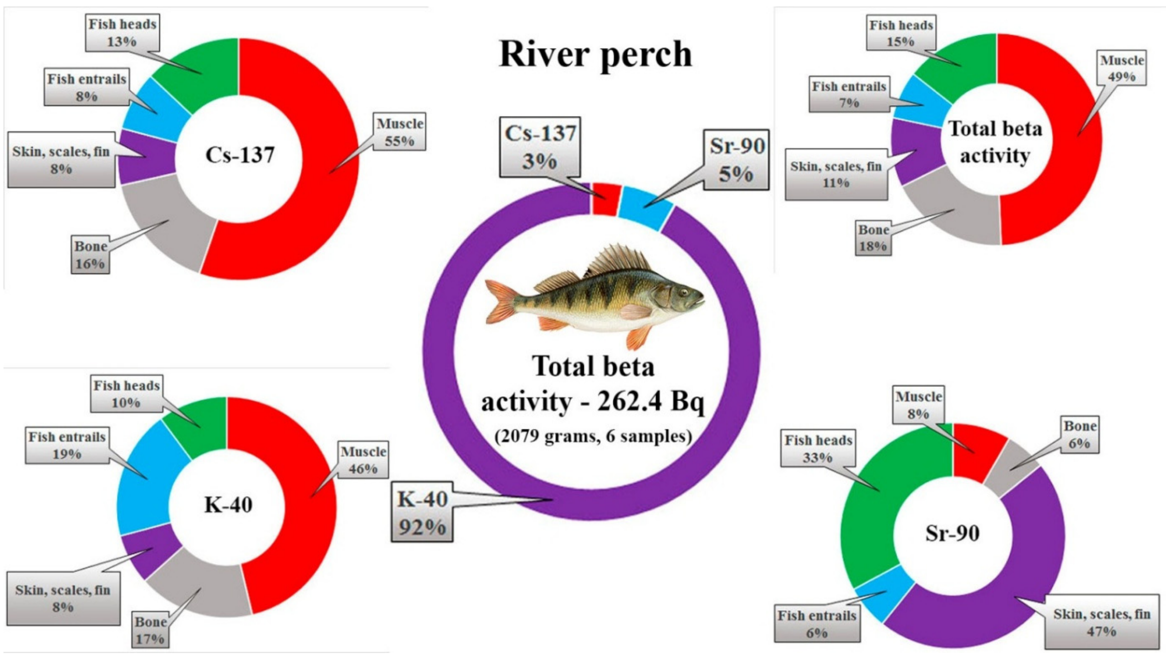

Fig. 2. Distribution of radionuclides in tissues of river perch (Nes River).

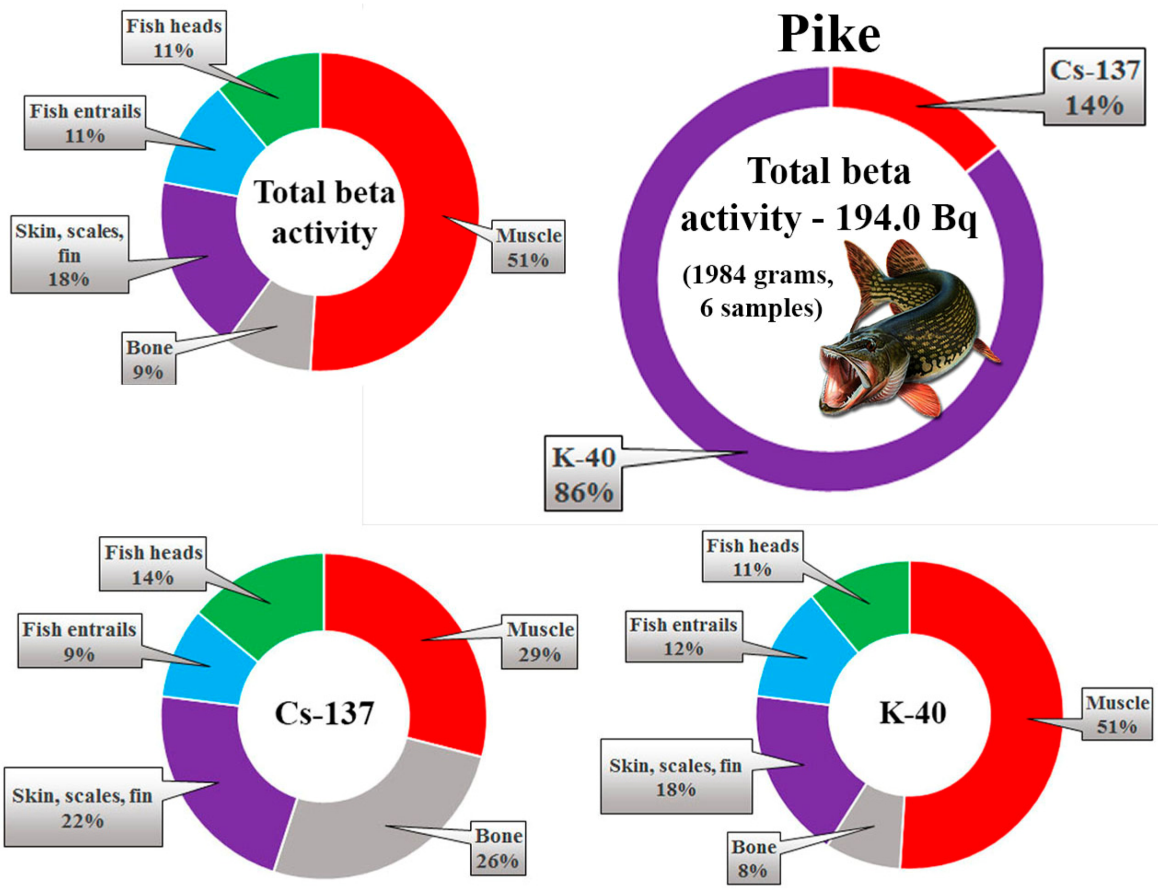

Fig. 3. Distribution of radionuclides in tissues of pike (Nes River).

samples.

The activity of the K-40 isotope varied within the following limits: from 94.3 to 136.2 Bq/kg for muscle tissue, from 91.3 to 131.3 Bq/kg for bone tissue, from 38.2 to 86.0 Bq/kg for a mixture of skin, scales and fins, from 44.4 to 173.6 Bq/kg for entrails, and from 51.0 to 70.1 Bq/kg for heads. The highest content of the isotope was found in the muscle tissue of fish from the Nes River (46% for perch and 51% for pike), as well as in a mixture of skin, scales, and fins in pike (18%) and bone tissue in perch (17%).

For the studied fish samples, the range of weight and length parameters was also determined. Thus, the length and weight of perch from the Nes River ranged from 219 to 349 g and from 24 to 28 cm, respectively. The length and weight of the pike from the Nes River ranged from 250 to 603 g and from 30 to 41 cm, respectively.

Research in the field of assessing the sources of radionuclides through the Sr-90/Cs-137 isotope ratio remains relevant. In the present study, the activity ratio of Sr-90/Cs-137 isotopes in whole fish samples taken from the Nes River was 0.27 for pike and from 1.39 to 1.97 for perch (Table 1). For organs and tissues of fish, the ratio of isotope activities was in the range of 0.07 to 10.8.

Analysis of the obtained results, their comparison with the results of other authors and scientific works, as well as the main conclusions, are given below in the "Discussions".

The results of the first stage of research showed that in only one studied river of the North-West of Russian Arctic, cesium and strontium radionuclides were found in fish - in the Nes River in the Nenets Autonomous Okrug.

Table 1. Isotopic ratios of Sr-90/Cs-137 in the tissues of fish (Nes River).

	Isotope ratio Sr-90/Cs-137, rel. units	
	Perch	Pike
Whole samples:	1.39 (first stage) 1.97 (second stage)	0.27
muscle	0.27	0.07
bone	0.64	0.44
skin, scales, fin	10.8	0.49
entrails	1.42	0.14
heads	4.47	0.83

Due to the absence of other short-lived radionuclides (e.g. Cs-134, Co-60), it can be concluded that there is a weak radiation anomaly in this territory based on the results of global radioactive fallout, in particular, nuclear weapons tests on the Novaya Zemlya archipelago. If we compare the obtained results with other scientific works in other regions, it can be noted that the activities of cesium and strontium in fish from the Nes River are slightly higher than in many other research papers (Hubanova et al., 2019; Friedlander et al., 2005; Trapeznikov et al., 2019; Zotina et al., 2011; Miki et al., 2017). According to the Arctic Monitoring and Assessment Program (Hubanova et al., 2019), various fish species contain lower concentrations of Cs-137, ranging from 0,09 Bq/kg in Dab (*Limanda limanda*) to 0.3 Bq/kg for Shorthorn sculpin and flounder. In the North Atlantic Region, Cs-137 activity values ranged from 0.3–0.5 Bq/kg (flounder, mackerel, and blue whiting) to 1.5 Bq/kg in cod and 2.2 Bq/kg in scad (Friedlander et al., 2005). For the Ob and Irtysh Rivers, Cs-137 activity in fish ranged from 0.6 to 1.9 Bq/kg (Trapeznikov et al., 2019), while in fish from the Yenisei River, the activity ranged from 0.6 to 4.9 Bq/kg (Zotina et al., 2011). An average Cs-137 level of 6.1 Bq/kg fw was observed in freshwater fishes harvested in the Experimental Lakes Area (ELA) in Ontario (Canada), almost twice that of samples measured in the National Capital Region of Canada and more than 20 times higher than the levels observed in marine fish harvested from the Canadian west coast (Chen et al., 2016). Higher concentrations of Cs-137 have been found in cod (range 6.44 to 8.86 Bq/kg) in the Irish and Baltic Seas (Friedlander et al., 2005). The muscle tissue of fish from the Savannah River (near the former nuclear weapons production facility in South Carolina, USA) contained Cs-137 from 1 Bq/kg (*Lepomis macrochirus*) to 10 Bq/kg (*Amia calva*), moreover, in the tributary of this river (Steel Creek) there was a fish with a radiocesium content of 80 Bq/kg in muscle tissue (*Micropterus salmoides*) (Burger et al., 2001). In fish from the Dnepropetrovsk reservoir, the content of Cs-137 ranged from 0.12 Bq/kg (crucian carp) to 15.1 Bq/kg (eastern bream) (Hubanova et al., 2019). High activities of Cs-137 were revealed in fish from the Techa River (range 24.9 to 98.4 Bq/kg) (Trapeznikov et al., 2019), and in the near-glacial zone near the Novaya Zemlya archipelago, a number of fish samples recorded extreme levels of Cs-137 activity, reaching 450–640 Bq/kg (Mirochnikov et al., 2017).

The same comparative picture is observed for Sr-90. A similar range of Sr-90 activities in fish was observed in fish of the Dnepropetrovsk reservoir: from 0.24 Bq/kg in roach and crucian carp to 37.5 Bq/kg in silver carp (Hubanova et al., 2019). For fish from the Irtysh and Ob Rivers, the content of Sr-90 varied from 6.0 to 8.1 Bq/kg (Trapeznikov et al., 2019), while for fish from the Techa River, high values of Sr-90 activity were found in the range from 1137.8 to 2023.0 Bq/kg. In marine fish off the coast of Japan within a radius of more than 20 km from the Fukushima Nuclear Power Plant, Sr-90 concentrations were <0.046 Bq/kg [Miki et al., 2017]. The concentration of strontium-90 in the fish from the Persian Gulf coastline (Iran, near the Bushehr nuclear power plant) was 0.252- 0.955 Bq/kg (Firouzabadi et al, 2020).

The content of the radionuclide K-40 varied within the range of activities similar to fish in other regions of the world (Alimova and Utkina, 2016; Milenkovic et al., 2019; Heldal et al., 2019). It is noted that a similar concentration of K-40 in fish was determined for marine fish from the North Atlantic (in the range from 32 to 152 Bq/kg) (Friedlander et al., 2005) and in Turkey (in the range from 35.04 to 127.41 Bq/kg) (Korkmaz et al., 2012). Higher K-40 activities were found in fish from Malaysia (in the range from 161.9 to 239.7 Bq/kg) (Saat et al., 2014) and in fish taken from the Yenisei River (in the range from 86 to 357 Bq/kg) (Zotina et al., 2011).

In the present study, the highest activity of Cs-137 and Sr-90 radioisotopes was noted for perch from the Nes River, while other fish species sampled from this river accumulated isotopes in smaller amounts. As noted in the scientific literature, the concentrations of radionuclides differ in different fish species, even when they were caught in the same fishing area, which indicates a different nature of radionuclide bioaccumulation (Bezhenar et al., 2021; Hubanova et al., 2019; Carvalho et al., 2011). Not only the aquatic environment but also the food chain are important sources of radionuclide accumulation by marine fish (Suzuki et al.,1979). It should be noted that perch is a predatory fish, while flounder, herring, and saffron cod feed on small crustaceans, plankton, and vegetation (Suzuki et al.,1979).

The prevailing majority of scientific literature data states that, in general, predatory fish accumulate more radionuclides compared to peaceful fish, which is associated with a higher trophic level of these species (Zotina et al., 2019; Rask et al., 2012; Ries et al., 2019; Wesley and Khan, 2011; Pearson et al., 2016; Ryabov, 2002). For example, the activity of Cs-137 and Sr-90 in the predatory fish species of the Pripyat River ranged from 22 to 224 Bq/kg and 1 to 16 Bq/kg, respectively, while in peaceful fish species, it ranged from 12 to 60 and from 3 to 13 Bq/kg, respectively (Kaglyan et al., 2016). Predatory fish from the Techa River contained 2023 Bq/kg of the Sr-90 radionuclide and 98.4 Bq/kg of the Cs-137 radionuclide, while peaceful fish contained a lower number of isotopes (1137.8 Bq/kg for Sr-90 and 24.9 Bq/kg for Cs-137) (Trapeznikov et al., 2019). Another possible reason for the higher content of Cs-137 and Sr-90 in perch is that it belongs to river fish, while flounder, herring, and saffron cod belong to marine fish. Radionuclide concentrations in freshwater fish may be elevated because, in freshwater ecosystems, low mineral content in the water results in higher radionuclide concentrations in freshwater fish compared to marine fish (Ryabov et al., 1998). This may be due to the function by which freshwater fish retain salts in their bodies, making it difficult for them to release radioactive nuclides (Fisheries Agency of Japan, 2014).

The results obtained on the identified technogenic radionuclides (Cs-137 and Sr-90) in fish from the Nes River show the need for additional studies of fish, as well as expanding the study area and the distribution of radionuclides in individual organs and tissues of fish species.

Absorbed elements are redistributed between organs and tissues (Bezhenar et al., 2021). Identification of the regularities in the distribution of radionuclides will make it possible to determine the danger of consuming the studied fish, since the muscle tissue of fish is the main product consumed by people for food. Therefore at the second stage, we studied the content of radionuclides in different organs and tissues of fish in the rivers Nes, Pechora (Nenets Autonomous District) and Mezen (Arkhangelsk Region). In this study, the Nes River is a key site due to the presence of artificial radionuclides. The Pechora and Mezen rivers are background areas in the presence of only K-40 radionuclide in fish.

The highest content of the Cs-137 isotope was observed for fish taken from the Nes River. The obtained results of measurements of total beta activity, as well as the activities of Cs-137, Sr-90 and K-40 in individual organs of fish, are similar in some cases to the results of studies in other regions of the world. Studies of the content of total β-activity in the fish organs of the Dnepropetrovsk reservoir also showed that the highest values were determined in bones (from 171.88 to 363.13 Bq/kg) and muscles (from 122.49 to 252.43 Bq/kg) (Hubanova et al., 2019). The alpha activity was not found in organs and tissues.

The main accumulation of the radioisotope Cs-137 in the muscle tissues of fish is also noted in the literature (Zotina et al., 2019; Miki et al., 2017; Kaglyan et al., 2016; Coughtrey and Thorne, 1983; Povinec and Hirose, 2015). As noted in (Yankovich, 2003; Bezhenar et al., 2021), 88% of the Cs-137 isotope accumulates in the muscles, 8% in the skeleton, and less than 3% in the liver. However, for fish in the Dnepropetrovsk Reservoir and Samara Bay, the highest Cs-137 concentration was determined for fish bone tissue (Ananieva and Shapovalenko, 2019). The concentrations of Cs-137 in the muscles and bodies of fish (grayling and pike) sampled in the Yenisei fluctuated at similar activity levels (Zotina et al., 2019).

The nature of the priority accumulation of Sr-90 in the inedible part of the fish is also confirmed by other studies (Hubanova et al., 2019; Miki et al., 2017; Kaglyan et al., 2016). As noted in a study (Yankovich, 2003), 64% of the Sr-90 isotope accumulates in the skeleton, 27% in the muscles, and less than 2% in the liver. In the Dnepropetrovsk reservoir, the highest values of Sr-90 were noted in the bones of fish (up to 3.80 Bq/kg), and the lowest values of Sr-90 were noted in the scales (up to 1.10 Bq/kg) and gills (up to 1.10 Bq/kg). Also, in the fish tissues of the Samara Bay, the highest concentrations of 90Sr were determined for bone tissue (up to 4.5 Bq/kg). It should be noted that since most Sr-90 is associated with bones, the doses of this isotope for people consuming only muscle tissue will be much lower (Fresquez et al., 1999).

According to the results of studies of the Dnepropetrovsk reservoir, the largest accumulation of K-40 in fish occurred in bone tissue (from 93.7 to 101.8 Bq/kg) and gills (from 81.2 to 117.4 Bq/kg) (Ananieva and Shapovalenko, 2019). The distribution of K-40 in the tissues of the fish of the Samara Bay shows that the highest content of K-40 was recorded in the muscles of perch – 134.50 Bq/kg and in the bone tissue of pike perch – 114.30 Bq/kg (Ananieva and Shapovalenko, 2019). The accumulation of K-40 mainly in bone tissues was noted in the work (Hubanova et al., 2019), where the activity of this isotope ranged from 0.89 Bq/kg in the muscles of crucian carp to 77.4 Bq/kg in the bones of the eastern bream (Dnepropetrovsk reservoir).

Based on the results of the fish weight assessment, we concluded that the perch was about 5-6 years old, and the pike was about 2-3 years old. In general, Sr-90 accumulation is observed in perch, while Cs-137 accumulates in young pike. The effect of fish size on radionuclide accumulation has been described for various aquatic systems (Zotina et al., 2019; Kaglyan et al., 2016). In the scientific literature, more intensive accumulation of Sr-90 radionuclides in the early periods of fish life is most often noted (Kaglyan et al., 2016). This is due to the fact that growing organisms require more calcium to build the skeleton than adults, and strontium accumulates along with calcium (Hubanova et al., 2019). Also, in studies (Zotina et al., 2019), the highest concentration of Cs-137 was found in the smallest (i.e. youngest) pike, indicating a negative "size effect". Since this study did not divide fish by size, the study of the "size effect" for fish from the Nes River is one of the tasks for further research.

To assess and understand the source of radionuclides in fish, it is possible to use isotope ratios, for example, Sr-90/Cs-137, which were studied in this scientific article. According to literature data, the activity ratio of Sr-90/Cs-137 in global fallouts is estimated at about 0.6 (Mirochnikov et al., 2017; Krey and Krajewsky, 1970). Lower isotope ratios for predatory fish were also found in the study (Kaglyan et al., 2016). Thus, the Sr-90/Cs-137 ratio in peaceful fish species in the Pripyat River ranged from 0.06 to 0.52, and in predatory fish – from 0.15 to 0.37. In some water bodies near the Chernobyl nuclear power plant, the ratio of Sr-90/Cs-137 for food fish species reached from 1.78 to 50.00, while for predatory fish – from 0.38 to 2.11 (Kaglyan et al., 2016). The value of the ratio of radioisotopes in fish off the coast of Japan before the Fukushima accident ranged from 0.06 to 0.38, while after the accident the ratio values were in the range from 0.002 to 0.010 (Miki et al., 2017).

The obtained results show that the Sr-90/Cs-137 isotopic ratio has a wide range, which does not make it possible to identify the source of contamination. To identify it, further comprehensive studies of a wide range of environmental objects in the Nes River basin are required. It should be noted that the territory of the Nenets Autonomous Okrug is poorly studied in the field of radioecology (Yakovlev et al., 2021). The most studied are the basins of the rivers Pechora (Nenets Autonomous Okrug) and Northern Dvina (Arkhangelsk region). The activity of artificial Cs-137 in bottom sediments of the Pechora River delta was low and did not exceed 2.2 Bq·kg^{-1}. Authors did not detect any radioactive Sr-90 in bottom sediments (Yakovlev et al., 2021). In the bottom sediments of the Severnaya Dvina estuary, which is the second largest in the region in terms of basin area after the Pechora, the average activity of Cs-137 was 1.8 Bq·kg^{-1} (Kiselev et al., 2018). In 2021-2022, the authors of this article carried out studies of the main components of the environment (bottom sediments, peat, soil) of the Nes River basin for the content of artificial radionuclides Cs-137 and Sr-90 (Puchkov et al., 2023). According to the results of the study, it was found that the activity of Cs-137 in soil reaches 295±28 Bq/kg (average activity 80.2 Bq/kg), in peat - 200±18 Bq/kg (average activity 70.0 Bq/kg) , bottom sediments - 36±8 Bq/kg (average activity 8.9 Bq/kg). The activity of Sr-90 in peat reaches 47±8 Bq/kg (average activity 38.3 Bq/kg). The authors did not study this radionuclide in bottom sediments and soil. It can be noted that the average activity of Cs-137 in the bottom sediments of the Nes River exceeds by several times the average activity of the radionuclide in the main rivers of the North-Western part of Russia - the Pechora and the Northern Dvina rivers. The activity of Cs-137 in the soil of the Nes River basin is 2-3 times higher than the same parameter in other regions of the Arkhangelsk region and the Nenets Autonomous Okrug (Kiselev et al., 2018, Bazhenov et al., 2022). Back in 2001, it was noted that individual soil samples of the Kanin Peninsula of the Nenets Autonomous Okrug are characterized by high values of Cs-137 activity - up to 2000 Bq / kg, which was associated with one of the possible traces after nuclear tests on the Novaya Zemlya archipelago (Баженов, диссертация, 2001). Based on the results of studying the spatial distribution of artificial radionuclides in the Nes River basin (Puchkov et al., 2023), it was found that the highest values of Cs-137 and Sr-90 activities in peat are located in the tundra lowland, while in the upland and transit zones there is a planar washout of radionuclides along the slopes, which ensures their entry into the estuary of the Nes River. This fact may cause their accumulation in the fish-man food chains. For example in the picture! a diagram of the peat sampling profile in the Nes River basin and the distribution of Sr-90 is given (Puchkov et al., 2023). The distribution pattern of Cs-137 is similar to that of Sr-90.

According to (Puchkov et al., 2023), the average value of the Sr-90/Cs-137 isotope ratio in peat samples in the Nes River basin was 0.501. According to literature data, the activity ratio of Sr-90/Cs-137 in global fallouts is estimated at about 0.6 [Il'in et al., 2017, Matishov, 2014]. The only assumption that can explain the presence of artificial radionuclides in small quantities in the fish of the Nes River is a possible radioactive trace resulting from global atmospheric fallout, including after nuclear tests on the Novaya Zemlya archipelago.

The presence of radionuclides in marine and river ecosystems can have negative consequences for human health if they enter the food chain through fish consumption (Abdullah et al., 2015; Gorür et al., 2012; Adeleye et al., 2020). Controlling the level of accumulation of technogenic radionuclides in fish is an important step in ensuring human safety (Trapeznikov et al., 2019). It is known that continuous exposure of tissues and organs to ionizing radiation from the decay of incoming radionuclides causes genetic mutations, induces cancer in bones and living tissues, such as the kidneys or brain, and affects the digestive and respiratory systems (Garnier-Laplace et al., 2004; Fasae and Isinkaye, 2018; Orosun et al., 2018; Canu et al., 2011; Burger and Lichtscheidl, 2019; Lee et al., 2018; Pătraşcu et al., 2017). Therefore, it is extremely important to assess the potential danger of fish that is consumed by the population in the northwestern part of the Arctic region of Russia.

In accordance with the Russian hygienic legislation (SanPiN 2.3.2.1078-01, 2001), the permissible levels of Sr-90 and Cs-137 activity in fish muscle tissue used for food purposes

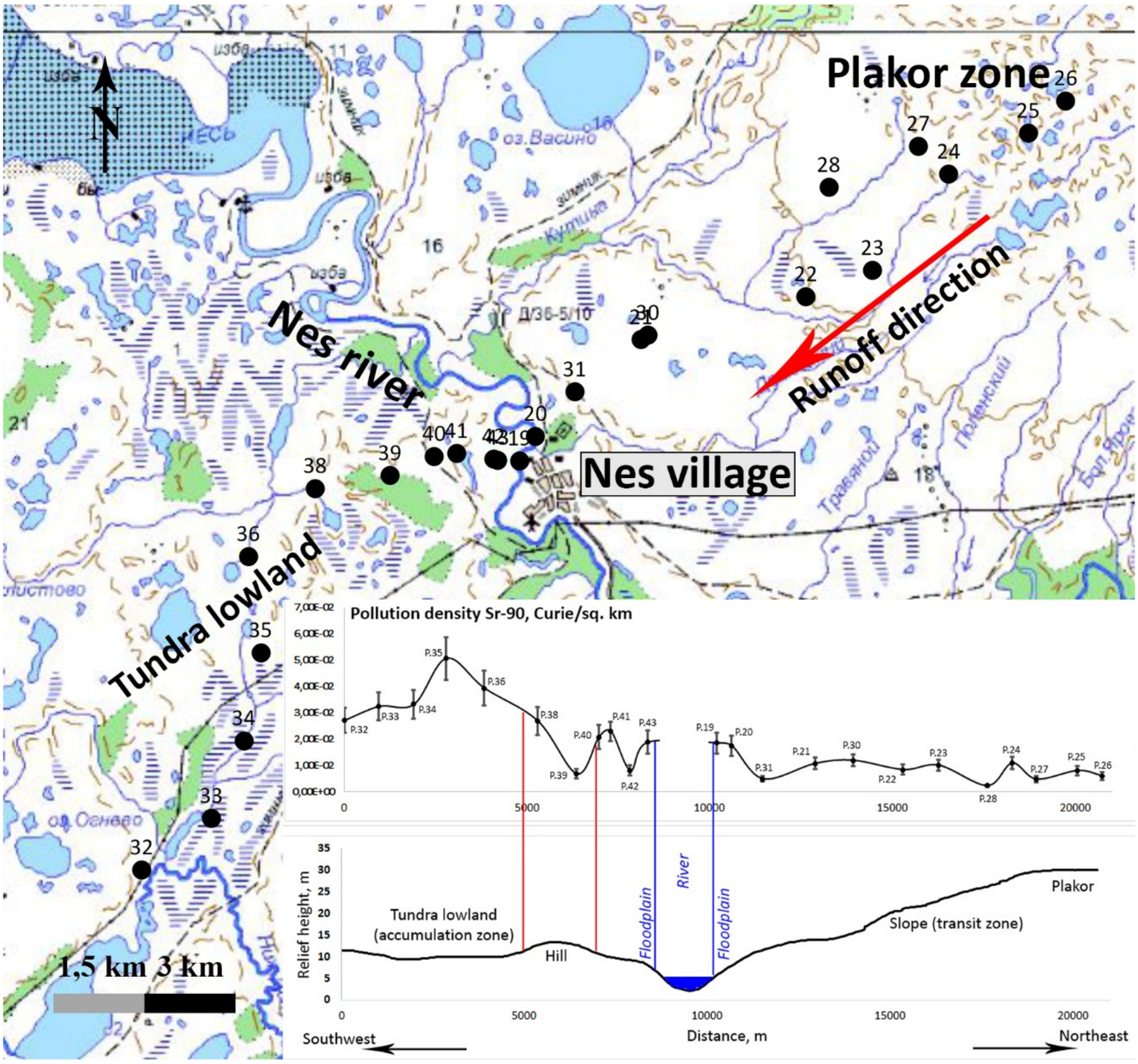

Fig. 4. Peat sampling scheme and spatial distribution of Sr-90 in the Nes river basin (Puchkov et al., 2023).

are limited to 100 and 130 Bq/kg, respectively. In this case, despite the relatively elevated values of Sr-90 and Cs-137 radionuclides in the Nes River, all the studied fish in the territory of the northwestern part of the Arctic region of Russia is suitable for human consumption.

It is noted that in 2017–2020, annual fish consumption rates for Russian regions, adjusted for the Barents Sea (Murmansk and Arkhangelsk), ranged from 20 to 46 kg fish muscle tissue in year (Kryshev et al., 2022). For this study, a survey was made of the population living near the rivers of the Nenets Autonomous District. The result of the survey showed that on average, a local resident consumed about 220 g of fish muscle tissue per day (80.3 kg fish muscle tissue in year). The high value of the annual consumption of fish is due to the fact that the main source of food in this area is fishing and hunting. Based on the data for fish muscle tissue, the ingestion doses from radionuclides reached the following values: 0.076 mSv/year for perch and 0.079 mSv/year for pike. It should be noted that the main contribution to the ingestion dose for muscle tissue was made by K-40 (88.7% for perch and 70.3% for pike), while the contribution of artificial radionuclides to the dose was 7, 2% for perch and 25.7% for pike (Cs-137), 4.1% for perch and 3.9% for pike (Sr-90). The calculated annual effective dose is below the limit of 1 mSv/year (Kryshev et al., 2022). Our result was also below the average radiation dose of

0.29 mSv/year, received per capita worldwide from naturally occurring radionuclides ingestion (UNSCEAR, 2000). In addition, our result is also below the dose limit of 0.25–0.40 mSv/year, recommended by the World Health Organization (WHO, 2011). Thus, it can be concluded that the current levels of increased radioactivity in fish from the Nes River do not pose a significant radiological risk to the local population (Fakhri et al., 2022).

CONCLUSIONS

As a result of studies in the tundra areas of the northwestern sector of the Russian Arctic, the presence of technogenic radionuclides Cs-137 and Sr-90 in predatory fish species (perch and pike) in the Nes River of the Nenets Autonomous District was revealed. At the same time, the fish of the White Sea, the Sukhoe Sea Bay, the Northern Dvina, Mezen, Pesha, Vizhas, Oma, and Pechora Rivers do not contain technogenic radionuclides, or their activities slightly exceed the MDA. The results of the study of organs and tissues of river perch and pike showed the accumulation of Cs-137 in muscle tissue in river perch (55%), in muscle and bone tissue in pike (29% and 26%, respectively), and Sr-90 in a mixture of skin, scales and fins (47%) and heads (33%). The main dose-forming radionuclide in all fish samples was the natural radionuclide K-40. The content of this radionuclide exceeded 86% of the total activity of beta-emitting radionuclides and corresponded to the average levels in fish from other regions. The only assumption that can explain the presence of artificial radionuclides in small quantities in the fish of the Nes River is a possible trace of radioactivity that occurred as a consequence of nuclear tests, including on the Novaya Zemlya archipelago. At the same time, it is noted that the current levels of increased radioactivity in fish from the Nes River do not pose a significant radiological risk to the local population. The conducted studies made it possible to initiate complex radioecological studies of the tundra territories of the Arctic zone of the Russian Federation, which are still underexamined.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication &/ or falsification, double publication &/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

APPENDIX A

Table A1. Fish weight range, activity of radionuclides in tissues and organs of fish from rivers of the North-West of Russian Arctic.

Fish species, **number of samples**	Tissue type	Sample weight, g	Activity, Bq/kg				
			β activity	α activity	Cs-137	Sr-90	K-40
Northern Dvina River (July 2019)							
Whitefish, 7 samples	Pooled samples	670	62.7±10.0	6.9±3.1	< 0.42	< 3.3	46.7±7.5
Bream 2 samples	Pooled samples	676	79.7±12.8	< 6.1	< 0.45	< 3.9	62.2±9.3
White Sea (June 2018)							
Smelt 25 samples	Pooled samples	1050	62.0±9.9	< 5.2	< 0.34	< 3.5	48.5±7.8
Whitefish 9 samples	Pooled samples	1049	79.9±12.8	< 4.3	< 0.41	< 2.5	67.5±9.5
Sukhoe Sea Bay (July 2019)							
Flounder 8 samples	Pooled samples	1162	49.2±7.9	6.1±3.0	1.33±0.48	< 3.3	32.9±5.6
Smelt 27 samples	Pooled samples	1082	71.2±11.4	< 3.3	< 0.29	< 3.6	59.1±7.9
Whitefish 8 samples	Pooled samples	807	96.0±15.4	< 3.4	< 0.30	< 2.9	81.3±10.6
Kerchak 12 samples	Pooled samples	1167	49.5±7.9	< 3.5	< 0.44	< 2.4	42.0±6.7
Saffron cod 5 samples	Pooled samples	267	103.0±16.5	< 3.7	< 0.34	< 2.4	90.7±12.7
Pesha River (March-June 2019)							
Perch, Flounder, Saffron cod	Pooled multispecies sample (14 samples)	1950	93.0±14.9	< 2.7	0.37±0.15	< 3.4	85.0±12.8
	Pooled multispecies sample (16 samples)	2320	91.0±14.8	< 2.5	0.22±0.10	< 2.4	80.6±12.9
	Pooled multispecies sample (10 samples)	1560	97.0±15.0	< 2.4	< 0.20	< 1.9	75.3±11.3
Oma River (March-June 2019)							
Perch, Flounder, Saffron cod	Pooled multispecies sample (9 samples)	1260	94.3±14.5	< 2.3	0.25±0.11	< 2.6	71.0±9.9
	Pooled multispecies sample (11 samples)	1570	67.8±10.8	< 2.7	0.32±0.14	< 2.3	59.9±9.6
	Pooled multispecies sample (10 samples)	1400	78.7±12.6	< 3.6	0.50±0.24	< 1.5	68.9±10.3
Vizhas River (March-June 2019)							
Perch, Flounder, Saffron cod	Pooled multispecies sample (10 samples)	1430	131.4±21.0	< 3.5	0.21±0.10	< 1.5	125.0±15.0
	Pooled multispecies sample (13 samples)	1860	125.7±20.1	< 2.8	< 0.15	< 1.9	110.1±13.2
	Pooled multispecies sample (13 samples)	1770	143.2±22.9	< 2.6	< 0.12	< 1.3	138.0±16.6
Nes River (March-June 2019)							
Flounder (5 samples)	Pooled samples	1260	119.0±19.0	< 2.6	< 0.24	< 4.9	109.3±13.1
Herring (55 samples)	Pooled samples	2750	112.6±18.0	< 3.4	< 0.16	< 6.9	114.7±13.8
Saffron cod (13 samples)	Pooled samples	1564	135.6±21.7	< 1.2	< 0.12	< 5.2	130.8±12.7
Perch	Pooled 6 samples	1070	140.5±22.5	< 3.1	11.7±2.2	23.1±6.7	101.2±12.1
	Pooled 5 samples	1120	124.7±20.0	< 2.4	13.4±2.3	18.6±5.6	89.3±11.6
Nes River (June 2020)							

Continued Table A1. Fish weight range, activity of radionuclides in tissues and organs of fish from rivers of the North-West of Russian Arctic.

Fish species, **number of samples**	Tissue type	Sample weight, g	Activity, Bq/kg				
			β activity	α activity	Cs-137	Sr-90	K-40
Perch, 6 samples (219-340 g each)	Pooled samples	2079	113.5±18.1	< 0.97	3.73±1.21	6.60±2.31	115.9±15.1
	Muscle tissue	820	142.1±22.7	< 0.97	5.22±0.99	< 1.4	136.2±17.7
	Bone tissue	349	124.5±20.0	< 4.8	3.60±1.01	< 2.3	118.0±14.2
	Skin, scales, and fins	295	85.3±13.6	< 12.6	2.00±0.68	21.67±4.55	61.2±9.2
	Fish entrails	264	65.3±10.4	< 2.3	2.32±077	< 3.3	173.6±20.8
	Fish heads	351	96.9±15.5	< 6.9	2.87±0.92	12.84±3.98	70.1±11.2
Pike, 6 samples (250-603 g each)	Pooled samples	1984	96.0±15.4	2.64±1.6	14.0±1.7	< 3.72	83.8±11.7
	Muscle tissue	753	129.0±20.6	< 1.1	19.5±2.1	< 1.39	112.1±14.6
	Bone tissue	107	151.8±24.3	< 3.2	17.9±2.0	< 7.80	131.3±17.1
	Skin, scales, and fins	341	101.1±16.2	< 5.8	14.8±1.9	< 7.20	86.0±12.0
	Fish entrails	448	48.2±7.7	< 0.54	6.85±1.31	< 0.93	44.4±2.3
	Fish heads	335	62.9±10.1	< 5.5	9.38±1.52	< 7.82	55.5±8.3
Pechora River (August 2020)							
Perch, 6 samples (710-800 g each)	Pooled samples	4533	79.05±12.65	< 4.29	< 0.28	< 4.21	77.0±11.6
	Muscle tissue	1320	105.2±16.8	< 5.20	< 0.21	< 1.30	102.3±13.3
	Bone tissue	360	105.4±16.9	< 5.88	< 0.46	< 7.64	101.6±13.2
	Skin, scales, and fins	1080	74.1±11.9	< 4.53	< 0.42	< 5.12	73.3±9.5
	Fish entrails	849	58.2±9.3	< 0.88	< 0.17	< 1.28	57.4±9.2
	Fish heads	924	56.4±9.0	< 5.2	< 0.24	< 8.67	53.8±8.6
Pike, 5 samples (2810 g each)	Pooled samples	13995	83.5±13.4	< 2.08	0.44±0.21	< 3.19	79.9±12.0
	Muscle tissue	5310	122.6±19.6	< 0.77	0.57±0.27	< 1.53	121.1±14.5
	Bone tissue	755	99.2±15.9	< 5.8	< 0.52	< 5.1	94.0±14.1
	Skin, scales, and fins	2405	41.6±6.7	< 1.99	< 0.33	< 3.32	38.2±7.6
	Fish entrails	3160	62.5±10.0	< 0.69	0.31±0.16	< 0.99	60.8±7.9
	Fish heads	2365	61.4±9.8	< 5.8	< 0.38	< 9.1	51.0±6.6
Ide, 8 samples (603-685 g each)	Pooled samples	5064	83.1±13.3	< 2.77	< 0.58	< 4.78	81.3±12.2
	Muscle tissue	2120	95.5±15.3	< 0.9	0.3±0.16	< 1.3	94.3±11.3
	Bone tissue	412	98.9±15.8	< 5.6	< 1.4	< 8.1	94.9±12.1
	Skin, scales, and fins	1240	77.1±12.3	< 5.8	< 0.6	< 8.5	76.2±11.4
	Fish entrails	440	79.9±12.8	< 0.59	< 0.5	< 1.9	76.3±11.6
	Fish heads	852	55.1±8.8	< 2.8	< 0.9	< 7.9	52.3±7.8
Roach, 7 samples (463-469 g each)	Pooled samples	3245	82.9±13.3	< 1.87	< 0.45	< 4.75	79.8±11.8
	Muscle tissue	1176	104.9±16.8	< 0.6	< 0.3	< 1.4	100.0±13.2
	Bone tissue	410	94.5±15.1	< 3.2	< 0.9	< 6.3	91.3±11.9
	Skin, scales, and fins	784	74.7±12.0	< 3.0	< 0.6	< 8.4	72.2±10.8
	Fish entrails	392	51.0±8.2	< 0.5	< 0.3	< 1.1	49.9±8.0
	Fish heads	483	58.5±9.4	< 3.1	< 0.3	< 8.6	57.6±9.8
Mezen River (August 2021)							
Pike, 3 samples (2360-3120 g each)	Pooled samples	8430	93.5±15.0	< 2.4	< 0.44	< 3.53	88.4±15.0
	Muscle tissue	3270	135.1±21.6	< 1.89	< 0.52	< 2.41	129.1±15.5
	Bone tissue	486	110.2±17.6	< 4.75	< 0.52	< 4.95	102.2±14.3
	Skin, scales, and fins	1494	55.1±8.8	< 2.35	< 0.33	< 4.03	48.7±7.8
	Fish entrails	1740	69.9±11.2	< 1.05	< 0.52	< 1.55	65.8±9.9
	Fish heads	1440	61.6±9.9	< 4.7	< 0.25	< 7.5	59.9±9.6
Perch, 6 samples (520-650 g each)	Pooled samples	3640	76.7±12.3	< 4.6	< 0.37	< 4.6	75.5±10.6
	Muscle tissue	960	93.4±14.9	< 4.00	< 0.31	< 2.10	95.4±13.4
	Bone tissue	240	96.2±15.4	< 4.92	< 0.50	< 6.50	92.6±12.0
	Skin, scales, and fins	890	72.2±11.6	< 5.05	< 0.51	< 6.10	70.6±9.2
	Fish entrails	740	69.5±11.1	< 3.12	< 0.30	< 2.42	65.4±9.2
	Fish heads	810	62.8±10.0	< 6.1	< 0.31	< 7.55	61.5±8.0

REFERENCES

Abdullah, A., Hamzah, Z., Saat, A., Wood, A. K. & Alias, M. (2015). Accumulation of radionuclides in selected marine biota from Manjung coastal area. AIP Conf. Proc., 1659; 050009.

Adel, M., Copat, C., Saeidi, M. R., Conti, G. O., Babazadeh, M. & Ferrante, M. (2018). Bioaccumulation of trace metals in b&ed Persian bamboo shark (Chiloscyllium arabicum) from the Persian Gulf: a food safety issue. Food Chem. Toxicol., 113; 198-203.

Adeleye, M. O., Oyebanjo, O., Gbenu, S. T. & Alayande, S. O. (2020). Activity concentration of natural radionuclides & assessment of the associated radiological hazards in the marine croaker (pseudotolitus typus) fish from two coastal areas of Nigeria. Sci. World J., 15(2).

Age-dependent doses to the Members of the public from intake of radionuclides – Part 5 compilation of ingestion & inhalation coefficients. ICRP Publication 72. Ann. ICRP 1996, 26(1); 1-91.

Ajayi, O. S., Fatile, E. O. & Dike, C. G. (2018). Radiological toxicity of some fish & meat tissues consumed in southwestern Nigeria. Hum. Ecol. Risk Assess., 24; 1151–1159.

Alimova, G. S. & Utkina, I. N. (2016). Contents Cs-137, & K-40 in bottom sediments & in fishes of r. Irtysh & r. Tobol. Inter. J. Appl. Fund. Res., 9; 101-104. (in Russ.)

Ananieva, T. & Shapovalenko, Z. (2019). The contents of artificial & natural radionuclides in tissues of the Percidae fish from the Dnipro Reservoir. Ukr. J. Ecology, 9(3); 304-308.

Bazhenov, A. V., Iglovsky, S. A. & Yakovlev, E. Yu. (2022). Technogenic radioactivity of soils in the area of the Morzhovsky lighthouse (Morzhovets Island, Arkhangelsk Region). Soils & environment, 5(4); e193. (in Russ.)

Bezhenar, R., Kim, K. O., Maderich, V., de With, G. & Jung, K. T. (2021). Multi-compartment kinetic-allometric model of radionuclide bioaccumulation in marine fish. Biogeosciences, 18; 2591–2607.

Burger, A. & Lichtscheidl, I. (2019). Strontium in the environment: review about reactions of plants towards stable & radioactive strontium isotopes. Sci. Total Environ., 653; 1458–1512.

Burger, J., Gaines, K. F., Peles, J. D., Stephens Jr., W. L., Shane Boring, C., Brisbin Jr., I. L., Snodgrass, J., Bryan Jr., A. L., Smith, M. H. & Gochfeld, M. (2001). Radiocesium in fish from the Savannah River & Steel Creek: potential food chain exposure to the public. Risk Analysis, 21(3); 545-559.

Canu, I. G., Jacob, S., Cardis, E., Wild, P., Ca¨er, S., Auriol, B., Garsi, J. P., Tirmarche, M. & Laurier, D. (2011). Uranium carcinogenicity in humans might depend on the physical & chemical nature of uranium & its isotopic composition: results from pilot epidemiological study of French nuclear workers. Canc. Cause Contr., 22; 1563–1573.

Carvalho, F. P., Oliveira, J. M. & Malta, M. (2011). Radionuclides in deep-sea fish & other organisms from the north Atlantic Ocean. ICES J. Mar. Sci., 68(2); 333–340.

Chen, J., Rennie, M. D., Sadi, B., Zhang, W. & St-Amant, N. (2016). A study on the levels of radioactivity in fish samples from the experimental lakes area in Ontario, Canada. Environ. Radioact., 153; 222-230.

Compendium of dose coefficients based on ICRP publication 60. ICRP publication 119. Ann. ICRP 2012, 41 (Suppl. l); 1-132.

Coughtrey, P. J. & Thorne, M. C. (1983). Radionuclide distribution & transport in terrestrial & aquatic ecosystems: A critical review of data. vol 2. (Rotterdam).

Dowdall, M., Gwynn, J. P., Moran, C., O'Dea, J., Davids, C. & Lind, B. (2005). Uptake of radionuclides by vegetation at a High Arctic location. Environ. Pollut., 133; 327–332.

Fakhri, Y., Sarafraz, M., Pilevar, Z., Daraei, H., Rahimizadeh, A., Kazemi, S., Khedher, K. M., Thai, V. N., Ba, L. H. & Khaneghah, A. M. (2022). The concentration & health risk assessment of radionuclides in the muscle of tuna fish: A worldwide systematic review & meta-analysis. Chemosphere, 289; 133149.

Fasae, K. P. & Isinkaye, M. O. (2018). Radiological risks assessment of 238U, 232Th & 40K in fish feeds & catfish samples from selected fish farms in Ado-Ekiti, Nigeria. J. Radiat. Res. Appl. Sci., 11; 317-322.

Firouzabadi, M., Jahromi, H. J. & Ardakani, H. A. (2020). Measurement of Strontium-90 in the Persian Gulf Fish by Extraction Chromatography with Sr-resin & Liquid Scintillation Counter. Iran South Med. J., 23(6); 541-553.

Fisheries Agency of Japan (2014). Report on the Monitoring of Radionuclides in Fishery Products (March 2011 – March 2014). (Tokyo: Fisheries Agency of Japan).

Fresquez, P. R., Kraig, D. H., Mullen, M. A. & Naranjo, L. Jr. (1999). Radionuclides & trace elements in fish collected upstream & downstream of Los Alamos national laboratory & the doses to humans from the consumption of muscle & bone. J. Environ. Sci. Health – B Pestic. Food Contam. Agric. Wastes, 34(5); 885-899.

Friedlander, B. R., Gochfeld, M., Burger, J. & Powers, C. W. (2005). Radionuclides in the marine environment: a CRESP science review. In Book Amchitka Independent Science Assessment: Biological & Geophysical Aspects of Potential Radionuclide Exposure in the Amchitka Marine Environment. Consortium for Risk Evaluation with Stakeholder Participation; Powers, C.W., Burger, J., Kosson, D., Gochfeld, M., Barnes, D., Eds. (New Jersey: Piscataway).

Garnier-Laplace, J., Gilek, M., Sundell-Bergman, S. & Larsson, C. -M. (2004). Assessing ecological effects of radionuclides: data gaps & extrapolation issues. J. Radiol. Prot., 24(4A); 139-155.

Giri, S., Singh, G., Jha, V. N. & Tripathi, R. M. (2010). Natural radionuclides in fish species from surface water of Bagjata & Banduhurang uranium mining areas, East Singhbhum, Jharkh&, India. Int. J. Radiat. Biol., 86(11); 946–956.

Gorür, K. F., Keser, R., Akcay, N. & Dizman, S. (2012). Radioactivity & heavy metal concentrations of some commercial fish species consumed in the Black Sea Region of Turkey. Chemosphere, 87; 356-361.

Gwynn, J. P., Dowdall, M., Davids, C., Selnæs, Ø. G. & Lind, B. (2004). The radiological environment of Svalbard. Polar Res., 23(2); 167–180.

Heldal, H. E., Volynkin, A., Komperod, M., Hannisdal, R., Skjerdal, H. & Rudiord, A. L. (2019). Natural & anthropogenic radionuclides in Norwegian farmed Atlantic salmon (Salmo salar). J. Environ. Radioact., 205-206; 42-47.

Hubanova, N., Horchanok, A., Novitskii, R., Sapronova, V., Kuzmenko, O., Grynevych, N., Prisjazhnjuk, N., Lieshchova, M., Slobodeniuk, O. & Demyanyuk, O. (2019). Accumulation of radionuclides in Dnipro reservoir fish. Ukrainian J. Ecol., 9(2); 227-231.

IAEA (1999). Radiological assessment of coastal marine sediment & water samples, Karachi Coast, Pakistan. IAEA-Research Contract PAK8127- Radiation & Isotope Application Division. (Pakistan: Pakistan Institute of Nuclear Science & Technology).

Il'in, G. V., Kasatkina, N. E., Moiseev, D. V. & Usyagina, I. S. (2017). Infrastructure Objects of the Nuclear Fleet as Sources of Radioactive Contamination of the Barents Sea: Waste Repository in Guba Andreeva. Atomic Energy, 122(2); 131-137.

Jensson, H., Strand, P., Tsaturov, Y. & Reiersen, L. (2004). AMAP Asssessment 2002: Radioactivity in the Arctic. (Oslo: AMAP).

Kaglyan, A. Ye., Gudkov, D. I., Klenus, V. G., Yurchuk, L. P., Nazarov, A. B., Pomortseva, N. A., Shirokaya, Z. O. & Shevtsova, N. L. (2016). Radionuclides in fish of the Chernobyl exclusion zone: species-specificity, seasonality, size- & age-dependent features of accumulation. Rad. Applic., 1(2); 110-113.

Kiselev, G. P., Kiseleva, I. M., Druzhinin, S. V. & Bazhenov, A. V. (2018). The radioactivity of bottom sediments of the delta of the Northern Dvina River. (Moscow, Institute of Oceanology). (in Russ.)

Korkmaz, G. F., Keser, R., Akcay, N. & Dizman, S. (2012). Radioactivity & heavy metal concentrations of some commercial fish species consumed in the Black Sea Region of Turkey. Chemosphere, 87; 356–361.

Krey, P. W. & Krajewsky, B. (1970). Comparison of atmospheric transport model calculations with observations of radioactive debris. J. Geophys. Res., 75; 2901–2908.

Kryshev, A. I., Sazykina, T. G., Katkova, M. N., Buryakova, A. A. & Kryshev, I. I. (2022). Modelling the radioactive contamination of commercial fish species in the Barents Sea following a hypothetical short-term release to the Stepovogo Bay of Novaya Zemlya. J. Environ. Radioact., 244-245.

Lee, S., Oh, J., Lee, K., Lee, J., Hwang, S., Lee, M., Kwon, E., Kim, C., Choi, I. & Yeo, I. (2018). Evaluation of abundance of artificial radionuclides in food products in South Korea & sources. J. Environ. Radioact., 184; 46–52.

Livingston, H. D. & Povinec, P. P. (2002). A Millennium Perspective on the Contribution of Global Fallout Radionuclides to Ocean Science. Health Phys., 82; 656-668.

Łokas, E., Mietelski, J. W., Ketterer, M. E., Kleszcz, K., Wachniew, P., Michalska, S. & Miecznik, M. (2013). Sources & vertical distribution of 137Cs, 238Pu, 239+240Pu & 241Am in peat profiles from southwestern Spitsbergen. Appl. Geochem., 28; 100–108.

Matishov, G. G., Matishov, D. G., Usyagina, I. S. & Kasatkina, N. E. (2014). Long-term dynamics of radioactive contamination in the Barents-Kara region (1960-2013). Dokl. Earth Sci., 458(4); 473–

479.
Miki, S., Fujimoto, K., Shigenobu, Y., Ambe, D., Kaeriyama, H., Takagi, K., Ono, T., Watanabe, T., Sugisaki, H. & Morita, T. (2017). Concentrations of 90Sr & 137Cs/90Sr activity ratios in marine fishes after the Fukushima Dai-ichi Nuclear Power Plant accident. Fish. Oceanogr., 26(2); 221-233.
Milenkovic, B., Stajic, J.M., Stojic, N., Pucarevic, M. & Strbac, S. (2019). Evaluation of heavy metals & radionuclides in fish & seafood products. Chemosphere, 229; 324-331.
Mirochnikov, Yu., Laverov, N. P.; Chernov, R. A., Kudikov, A. V., Ysacheva, A. A., Semenkov, I. N., Aliev, R. A., Asadulin, E. E. & Gavrilo, M. V. (2017). Radioecological Research on the North Novaya Zemlya Archipelago. Oceanology, 57(1); 227-237. (in Russ.).
Muratov, O. E., Tichonov, M. N. & Rylov, M. I. (2014). Nuclear-radiation legacy in the north-west of Russia: ensuring nuclear & radiation safety, role of the public. Radiat. Saf.; 34-45. (in Russ.)
Ohtsuka, Y., Kakiuchi, H., Akata, N., Takaku, Y. & Hisamatsu, S. (2013). Daily Radionuclide Ingestion & Internal Radiation Doses in Aomori Prefecture, Japan. Health Physics., 105(4); 340-350.
Orosun, M. M., Adisa, A. A., Akinyose, F. C., Amaechi, E. C., Ige, O. S., Ibrahim, B. M., Martins, G., Adebanjo, G. D., Oduh, O. V. & Ademola, O. J. (2018). Measurement of Natural Radionuclides Concentration & Radiological Impact Assessment of Fish Samples from Dadin Kowa Dam, Gombe State Nigeria. African J. Med. Phys., 1(1); 25-35.
Pătraşcu, V., Mărgineanu, R. M., Maximov, V., Blebea-Apostu, A. -M., Galaţchi, M., Gomoiu, C. & Ţiganov, G. (2017). Radioactive Content in Fish from Black Sea Caches. Its Impact on Population by Food Consumption. In Book Diversity in Coastal Marine Sciences. (Switzerland: Springer Cham).
Pearson, A. J., Gaw, S., Hermanspahn, N. & Glover, C. N. (2016). Activity concentrations of 137Caesium & 210Polonium in seafood from fishing regions of New Zealand & the dose assessment for seafood consumers. J. Environ. Radioact., 151; 542–550.
Pinder, J. E., Hinton, T. G., Taylor, B. E. & Whicker, F. W. (2011). Cesium accumulation by aquatic organisms at different trophic levels following an experimental release into a small reservoir. J. Environ. Radioact., 102; 283–293.
Povinec, P. P. & Hirose, K. (2015). Fukushima radionuclides in the NW Pacific, & assessment of doses for Japanese & world population from ingestion of seafood. Sci. Rep., 5; 9016.
Puchkov, A. V. & Yakovlev, E. Yu. (2023). Features of accumulation & migration of technogenic radionuclides 137Cs & 90Sr in the tundra landscapes of the Russian Arctic (on the example of the Nes river basin, Kaninskaya tundra). Bull. Geosci. Accepted for publication. (in Russ.)
Rask, M., Saxén, R., Ruuhijärvi, J., Arvola, L., Järvinen, M., Koskelainen, U., Outola, I. & Vuorinen, P. J. (2012). Short- & long-term patterns of 137Cs in fish & other aquatic organisms of small forest lakes in southern Finl& since the Chernobyl accident. J. Environ. Radioact., 103; 41–47.
Ries, T., Putyrskaya, V. & Klemt, E. (2019). Long-term distribution & migration of 137Cs in a small lake ecosystem with organic-rich catchment: a case study of Lake Vorsee (Southern Germany). J. Environ. Radioact., 198; 89–103.
Ryabov, I. N. (2002). Long-term observation of radioactivity contamination in fish around Chernobyl. In Book Recent Research Activities about the Chernobyl NPP Accidentin Belarus, Ukraine & Russia. (Tokyo: Kyoto University).
Ryabov, I. N., Belova, N. V. & Polyakova, N.I. (1998). Evolution of radiocaesium contamination in fishes after the Chernobyl accident. Ital. J. Anim. Sci., 65(1); 455-460.
Saat, A., Isak, N. M., Hamzah, Z. & Wood, A. K. (2014). Study of Radionuclides Linkages Between Fish, Water & Sediment In Former Tin Mining Lake In Kampung Gajah, Perak, Malaysia. Malaysian J. Anal. Sci., 18(1); 170–177.
SanPiN 2.3.2.1078-01 (2001). Hygienic Requirements for Food Safety & Nutritional Value of Food Products. State Sanitary Rules & Regulations. (Russia, Moscow: Publishing Department of the Federal Center for State Sanitary & Epidemiological Surveillance of the Ministry of Health of Russia). (in Russ.)
Smith, J. N., Ellis, K. M., Polyak, L., Ivanov, G., Forman, S. L. & Moran, S. B. (2000). 239,240Pu transport into the Arctic Ocean from underwater nuclear tests in Chernaya Bay, Novaya Zemlya. Cont. Shelf Res., 20(3); 255–279.
Strand, P., Howard, B. J., Aarkrog, A., Balonov, M., Tsaturov, Y., Bewers, J. M., Salo, A., Sickel, M., Bergman, R. & Rissanen, K. (2002). Radioactive contamination in the Arctic–sources, dose assessment & potential risks. J. Environ. Radioact., 60; 5–21.
Suzuki, Y., Nakahara, M., Nakamura, R. & Ueda, T. (1979). Roles of Food & Sea Water in the

Accumulation of Radionuclides by Marine Fish. Bull. Japan. Soc. Scient. Fsher., 45(11); 1409-1416.
Thomas, D. M., Lee, C.-S. & Fisher, N. S. (2018). Bioaccumulation & trophic transfer of 137Cs in marine & freshwater plankton. Chemosphere, 209; 599–607.
Trapeznikov, A. V., Trapeznikova, V. N., Korzhavin, A. V., Nikolkin, V. N. & Plataev, A. P. (2019). Basic principles for assessing the safety of fish products from the ponds exposed to the influence of nuclear fuel cycle enterprises. Medico-Biological & Socio-Psychological Problems of Safety in Emergency Situations, 1; 106–114. (in Russ.).
UNEP/IAEA (1992). Assessment of the state of pollution of the Mediterranean Sea by radioactive substances. MAP Technical Report Series No. 62. (Athens: UNEP).
UNSCEAR (2000). Sources & Effects of Ionizing Radiation. Report to the General Assembly with Annexes. (New York: United Nations).
Wesley, S. G. & Khan, M. F. (2011). Radionuclides in south Indian seafoods: A special focus on major contributing species. Radioprotection, 46(6); 151–159.
WHO (2011). The International Food Safety Authorities Network (INFOSAN), World Health Organization Food & Agriculture Organization progress report 2004– 2010. (Geneva: United Nations).
Yakovlev, E., Druzhinina, A., Druzhinin, S., Zykov, S. & Ivanchenko, N. (2022). Assessment of physical & chemical properties, health risk of trace metals & quality indices of surface waters of the rivers & lakes of the Kola Peninsula (Murmansk Region, North-West Russia). Environ. Geochem. Health, 44(8); 2465-2494.
Yakovlev, E. & Puchkov, A. (2020). Assessment of current natural & anthropogenic radionuclide activity concentrations in the bottom sediments from the Barents Sea. Mar. Pollut. Bull., 160; 11151.
Yakovlev, E., Puchkov, A. & Bykov, V. (2021). Assessing the natural & anthropogenic radionuclide activities of the Pechora River estuary: Bottom sediments & water (Arctic Ocean Basin). Mar. Pollut. Bull., 172; 112765.
Yankovich T. L. (2003). Towards an improved ability to estimate internal dose to non-human biota: development of conceptual models for reference non-human biota. Proceedings of third international symposium on the protection of the environment from ionising radiation, IAEA, Vienna, Austria; 365–373.
Zotina, T., Trofimova, E. & Bolsunovsky, A. (2011). Artificial radionuclides in fish fauna of the Yenisei River in the vicinity of the Mining-&-Chemical Combine (Siberia, Russia). Radioprotection, 46(6); 75–78.
Zotina, T. A., Trofimova, E. A. & Dementyev, D. V. (2019). Time-dependent trends of artificial radionuclides in biota of the Yenisei River (Siberia, Russia). J. Environ. Radioact., 208-209; 106028.